GEOLOGY AND ORE DEPOSITS OF JOHNNY M MINE, AMBROSIA LAKE DISTRICT

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Abstract

The Johnny M mine is one of very few mines in the Ambrosia Lake district with uranium ore in two members of the Morrison Formation (Jurassic); these members are the Westwater Canyon Sandstone and the Brushy Basin Shale. The Westwater Canyon ore is contained in the two upper sandstone units of the member, and the Brushy Basin ore is contained in the Poison Canyon sandstone (informal usage). The sedimentary features and structures in the Westwater Canyon sandstones indicate that the sediments were deposited by a system of aggrading braided streams, possibly at the distal end of coalescing alluvial fans. The Poison Canyon sandstone was probably the result of deposition in a complex environment of meandering and braided streams. Paleocurrent-direction indicators, such as fossilized-log orientation, foreset azimuths, and the axes of crossbeds and channel scours, suggest that the local paleostream flow was to the east and southeast. The uranium mineralization is closely associated with 1) local accumulations of carbonaceous (humate) matter derived from the decay of organic material and 2) paleostream channels preserved in the rocks. The ore elements were derived from the leaching of volcanic air-fall tuffs and ash, which were introduced into the fluvial system during volcanic activity in the western United States. The mobile ore-element ions were reduced and concentrated by humic acids and bacteria present in the fluvial system and ultimately remobilized into the forms present today. The uranium is thus envisioned as forming either essentially on the surface as the sediments were being deposited or at very shallow depth.

Introduction

The Johnny M mine, operated by Ranchers Exploration and Development Corporation, is situated at the southeast edge of the Ambrosia Lake district, in secs. 7 and 18, T. 13 N., R. 8 W., McKinley County, New Mexico. The mine is easily accessible via NM-53.

Ranchers drilled the first hole in sec. 7 in 1968. By the end of 1971, 268 holes were drilled, logged, and the north side (sec. 7) orebodies were delineated (Fitch, this volume). The orebodies in sec. 18 (south side) were initially drilled out by United Nuclear Corporation and sold to Ranchers in 1970 (figs. 1a, b).

The shaft for the Johnny M mine (named for its discoverer, John E. Motica) was started in 1972 and finally completed in August 1974. The first pound of uranium ore was recovered in May 1976, and full production was reached during the summer of 1977. Total reserve estimates are about 3.5 million lbs U_3O_8.

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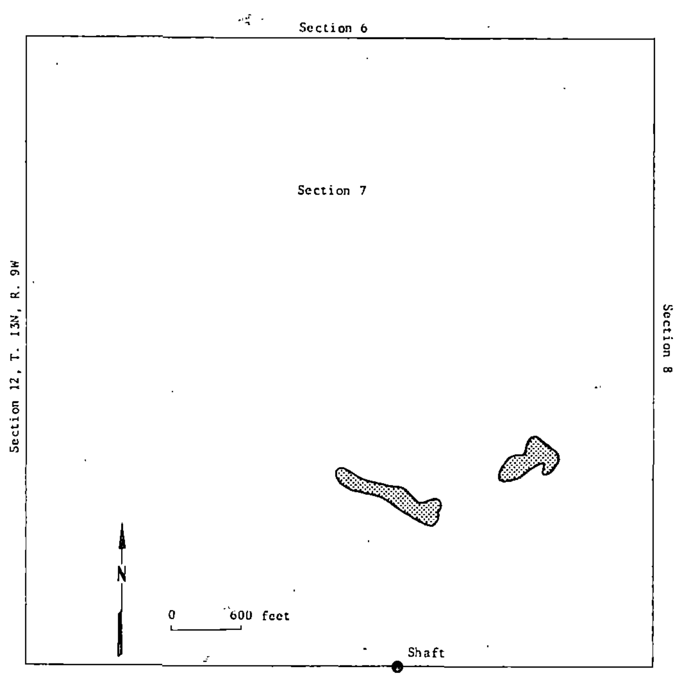

FIGURE 1a—NORTH-SIDE OREBODIES.

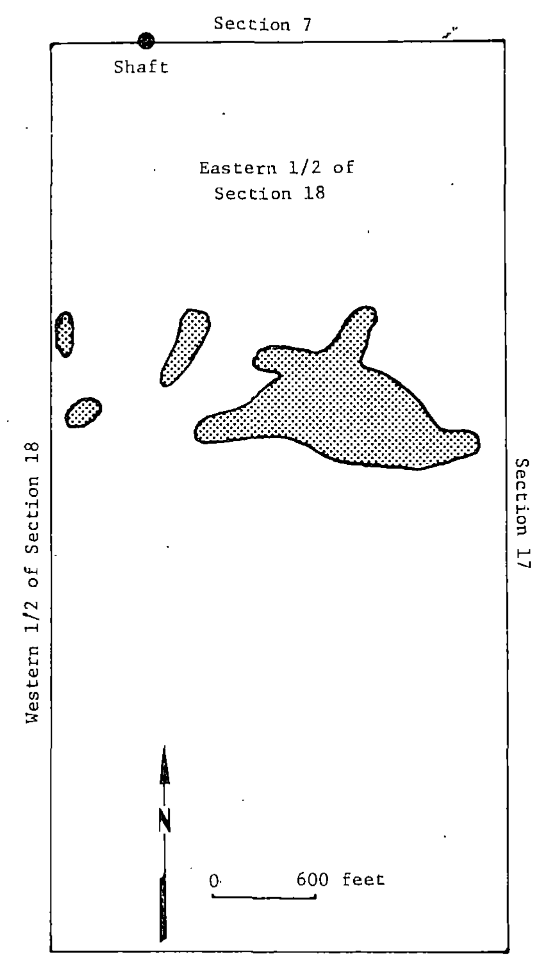

FIGURE 1b—SOUTH-SIDE OREBODIES.

General geology

Stratigraphy

The Johnny M is one of very few mines in the Ambrosia Lake district with uranium ore in two members of the Morrison Formation (Jurassic)—the Westwater Canyon and Brushy Basin Members. The Westwater Canyon ore is contained in the upper two sandstone units of the member (A and B horizons in fig. 2), and the Brushy Basin ore is contained in the informally designated Poison Canyon sandstone.

In the vicinity of the mine, the Westwater Canyon Sandstone averages 155 ft (51 m) in thickness, whereas the Brushy Basin Shale averages 110 ft (36 m). The A and B horizons of the Westwater Canyon vary in thickness throughout the area, but near the orebodies they average about 20 ft (7 m). Separating these sandstone horizons is usually a shale zone, often referred to as the K1 shale, which is fairly continuous and is about 12 ft (4 m) thick.

The Westwater Canyon and Brushy Basin are separated by a continuous shale layer known as the K shale. This layer is very similar to the main Brushy Basin shale and is considered the lowest shale unit of the Brushy Basin. The thickness is relatively uniform, commonly 8-12 ft (3-4 m).

The Poison Canyon sandstone, which rests directly on the K shale, tapers from 70 ft (23 m) thick in the northern part of sec. 7 to a feather edge in the southern part of sec. 18. Where the Poison Canyon is mined, its thickness is approximately 12 ft (4 m).

Above the Poison Canyon sandstone is the main shale zone of the Brushy Basin. Thickness varies, but it averages 90 ft (30 m) near the orebodies. Thickness is greater where the Poison Canyon sandstone is thin and vice versa.

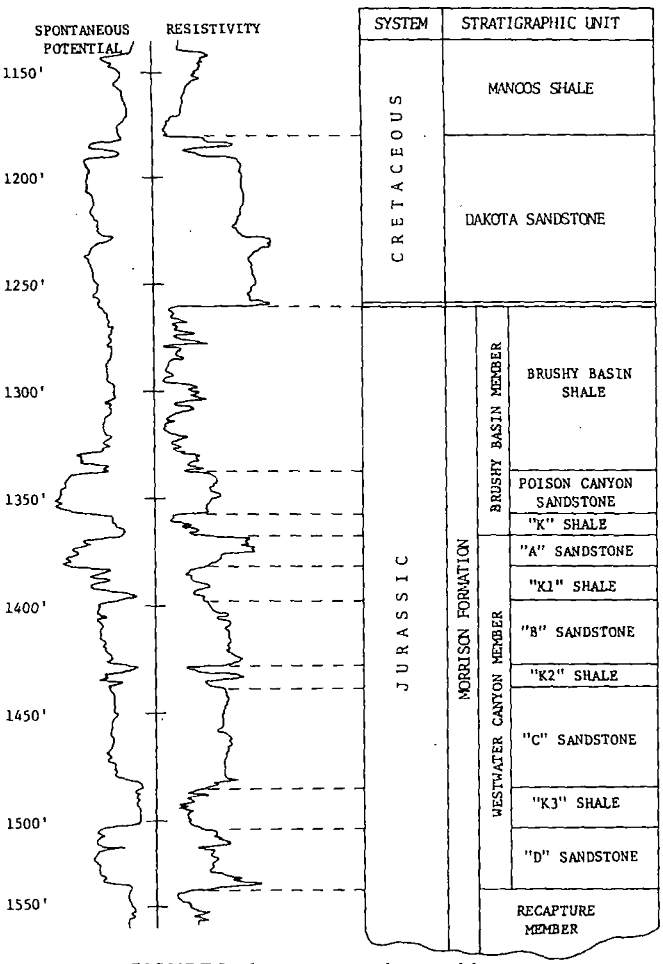

FIGURE 2—Log from the Johnny M mine.

Westwater Canyon Sandstone

SANDSTONE—The sandstones of the upper Westwater Canyon are arkosic; feldspars comprise about 35 percent of the rock. The sandstone layers may be horizontally bedded or complexly crossbedded. The crossbedding is associated with scour-and-fill structures, foreset development, and erosion surfaces or diastems that extend laterally for distances of up to 50 ft (16 m).

Sandstone varies unpredictably from weakly to strongly indurated (principally cemented by calcite) and varies widely in grain size, sorting, and roundness. Changes in texture and structure within beds and from one bed to another are common. Claystone fragments up to 2 inches (5 cm) in length are dispersed in some of the coarser grained sandstone units. Claystone-cobble conglomerates 1-2 ft (30-60 cm) thick are fairly common along diastems.

Plant remains and fossil trees and bones are especially widespread in the Johnny M mine. Fragments of logs, branches, and twigs are abundant, along with separate accumulations of leaves and reed-like plant stems. The smaller pieces are usually coalified, whereas the larger logs are commonly silicified. Dinosaur bones are also abundant.

The proportions of detrital minerals in the Westwater Canyon sandstones of the mine vary within wide limits; feldspar is usually between 25 percent and 40 percent of the total, with quartz composing most of the remainder.

Quartz, on the average, makes up 61 percent of the detrital minerals, but can range from 35 to 71 percent. Most grains are clear and free of fractures, but some have inclusions of dust and a rare bubble. The extinction patterns commonly are uniform, but locally a strained pattern is observed. Quartz overgrowths are not common. The roundness of the grains varies from rare, singly terminated crystals to extremely well-rounded grains, but most fall between subangular and subrounded (0.3 to 0.5 on the chart of Krumbein and Sloss, 1955). The grain size rarely exceeds 1.5 mm.

Orthoclase composes 13 percent of the detrital minerals. The orthoclase is commonly cloudy, more rounded than quartz, and fractured. Occasionally, some alteration (probably to sericite) is seen along the borders. Grain sizes are similar to those of quartz, although orthoclase grains average larger. Grain shapes range from angular (rare) to rounded, with the typical grain between subangular and subrounded.

Microcline is conspicuous in hand specimen as large pink grains and composes 8.5 percent of the detrital fraction. Microcline grains are usually very fresh, only rarely showing clay alteration. Polysynthetic (gridiron) twinning, characteristic of microcline, is very well developed. Microcline grains are usually larger than adjacent grains of other minerals and may be as large as 20 mm. Angular crystal laths are fairly common. The average microcline grain commonly is subangular to subrounded.

Plagioclase feldspar (14.5 percent of the detrital minerals) in the Westwater Canyon sands is sodic. Extinction angles on albite twinning for crystals cut normal to {010} range from 18 to 30 degrees, with the majority of the angles between 20 and 25 degrees (Michel-Levy method). This range, along with a positive optic sign, indicates that the plagioclase is principally in the composition range An_{30-50}, primarily andesine. The grains are very finely twinned, but no zoning was observed. Plagioclase is more intensely altered than potash feldspar, with many grains being completely covered by a thin layer of alteration clay, probably kaolinite or smectite. The grain shapes and sizes are comparable to those of microcline, except that the upper size limit is 2-3 mm. A few grains of antiperthite are present.

About 3 percent of the sandstone particles are rock fragments, mostly chert, with subordinate volcanic, granitic, limestone, and quartzite fragments. Chert grains, which may be as large as 15 mm in diameter, are often conspicuous in hand specimen. Rare volcanic detritus consists mostly of semispherical masses of low-birefringent clay minerals. A few identifiable sanidine grains are present, although almost completely dissolved, leaving an empty shell (see Austin, this volume).

Biotite and chlorite are present but uncommon in the 30 thin sections examined. Biotite appears slightly altered, and the chlorite exhibits anomalous blue interference color.

The only detrital heavy mineral identified was apatite, and this was present in only one thin section. Magnetite and ilmenite are conspicuously absent from these sandstones. Pyrite, heavily altered to hematite but showing cubic form, is not abundant.

CLAYSTONE—Claystone, which is present in layers interbedded in the sandstones, occurs in various shades of green and red. Fresh claystone is commonly dark green, whereas weathered claystone is a light grayish green, with irregularly shaped reddish lenses. Weathered claystone is very fragile and powdery, breaking up when handled. Fresh, dry claystone is blocky, having a smooth, almost soapy feel with little grittiness and a waxy sheen; it is usually sectile. The claystone consistently contains a small proportion of nonclay detrital particles, and the balance is composed of fine-grained clay minerals probably derived from alteration of volcanic ash.

A variety of textures exists in thin sections of the claystone. They commonly contain up to 10-15 percent subangular, fine-sand-size quartz and feldspar particles. These coarser particles are most frequently scattered randomly through the clay but may be concentrated in very fine laminae. Clay-particle outlines are indistinct, even at magnifications of 100×. Some orientation of the clay particles is indicated by a tendency to show extinction parallel to the bedding in polarized light.

A very interesting feature of the claystone zones is a mantling of colors on individual clay galls. A common feature is galls a foot across, with a red core and a green mantle. The inverse color scheme, a green core with a red mantle, is also observed but not as commonly.

AUTHIGENIC MINERALS—Kaolinite, calcite, barite, pyrite, and silica compose the suite of authigenic minerals. Kaolinite is pervasive throughout the mine, occurring in all sandstone horizons. The kaolin occurs as disseminated blebs or nests, ranging in size from a few millimeters to a couple of centimeters. These nests are composed of clean, white, well-crystallized kaolinite, filling the interstices of the sandstones and frequently surrounding several sand grains. Nests are disseminated throughout all the sands, but they are larger and more abundant in the coarser-grained sands. The nests may either be distributed randomly in the sands or follow sedimentary structures, such as bedding; where the nests are layered, the appearance is more that of a linear belt than that of a series of individual blebs.

Kaolinite nests may occupy as much as 5 percent of the volume of the sandstone; kaolinite makes up about 40 percent of the volume within a particular bleb. Kaolinite also has been observed filling very small, narrow fractures in sandstone, filling cracks in carbonized wood, or coating smaller pieces of carbonized fossils.

Calcite, in addition to acting as the major cementing agent, occurs as small rhomb-shaped crystals filling fractures within the sandstones and claystones. Crystals typically are clear and well defined and may be as large as a centimeter across. Calcite is also present in cracks in fossil trees and bones.

Barite occurs as honey-colored, tabular crystals up to a centimeter long and is limited to fractures in sandstones and claystones that occur in and near ore. The most visible barite crystals occur where the fracture crosses the ore pod, but they are also present along the fracture away from the ore. Occasionally the crystals are coated with a very thin layer of uranium mineralization.

Pyrite is not particularly abundant in the Westwater Canyon sands exposed in the mine. It may be present in fractures, ore-bearing sandstones, barren sandstones, and claystones. The form is typically that of very small cubes arranged in pockets as a thin dusting perched on detrital grains in the sandstone. The presence of the cubes is revealed by their high reflectance. The pyrite exposed on the mine-workings surface is typically fresh with no hematitic staining around or in the clusters.

Silica overgrowths on detrital quartz grains are pervasive throughout the mine and are locally abundant, but they actually make up a very small fraction of the total rock. Overgrowths may be present on every quartz grain in a particular area, and they impart a characteristic sparkle to the rock. More commonly they occur only on isolated grains.

Silica also occurs in the form of silicified wood and bones, which are widespread and abundant. The larger detritus, such as trees and bones, are always silicified, either completely or in the center, surrounded by a carbonized periphery. Smaller fragments are commonly carbonized.

Poison Canyon sandstone

The informally designated Poison Canyon sandstone is a gray to tan, generally poorly sorted, medium- to very coarse grained, locally conglomeratic sandstone. The general composition is that of an arkose, with feldspars composing about 30 percent of the detrital grains.

The Poison Canyon sandstone typically is horizontally bedded with thin laminae of very coarse clastics interbedded with the finer material, but in places it is complexly crossbedded. Cementing agents, mostly calcite, are irregularly distributed, yielding areas of friable sandstone and other areas that are very well indurated. Grain size and degree of roundness and sorting may vary considerably within beds, or from one bed to another. Claystone fragments are present along the bedding planes of the coarser material but are not nearly as abundant as in Westwater Canyon sandstones. Larger claystone fragments, up to 20 cm long, are irregularly dispersed but rare throughout the sand horizon.

Organic debris, abundant in Westwater Canyon sands, is virtually nonexistent in the Poison Canyon sands. Trash piles (Squyres, 1970) do not appear here, and small pieces of carbonized plants and trees are rarely encountered.

Quartz is by far the most abundant mineral in the Poison Canyon sandstone, composing 69 percent of the detrital minerals. The amount of quartz is fairly consistent, ranging from 60 percent to 76 percent. Quartz grains are clear and fracture free, with rare inclusions or bubbles. Uniform extinction patterns are the rule, with only a very small number of grains exhibiting a strained pattern. As might be expected in a fluvial system, the roundness of the grains varies, but most of the grains fall between subangular and subrounded (0.3 to 0.5 on the chart in Krumbein and Sloss, 1955), with a general tendency towards the subrounded category. The size of the quartz grains rarely exceeds 15 mm.

The second most abundant mineral is orthoclase, which composes 20 percent of the detrital minerals. Orthoclase grains are cloudier than quartz grains (due to alteration); they also contain some fractures. Sericite, an alteration product, is present along the borders of some of the grains. The orthoclase grains tend to be a little larger than the quartz and are also more rounded. Grain shapes range from subangular to rounded, with most of the grains being subrounded. Perthite is irregularly present.

Microcline, often the largest grains in hand specimen, composes 4.5 percent of the detrital minerals in the Poison Canyon sandstone exposed in the mine. Microcline grains are very fresh, with prominent polysynthetic (gridiron) twinning. Angular crystal laths are fairly common, with grains up to 20 mm in diameter. The majority of the grains are subangular to subrounded, with most being subrounded.

Plagioclase feldspar makes up 4.5 percent of the detrital minerals. The extinction angles observed on the albite twinning range from 19 to 28 degrees, and the optic signs are positive, indicating that the plagioclase is andesine. Twinning is coarser than in the Westwater Canyon sands; no zoning was observed. Many grains are altered and thinly covered with a clay, probably kaolinite or smectite. Lath-shaped grains are common, and most grains are subangular to subrounded. Grains rarely exceed 4 mm in diameter.

About 2 percent of the sandstone particles are rock fragments, mostly chert, with some granitic clasts and volcanic detritus. Chert grains are commonly rounded and may be as large as 15 mm across. The volcanic detritus is similar to that encountered in the Westwater Canyon sands, being spherical masses of undifferentiable clay minerals. Sanidine grains are rare, and the visible ones have largely been dissolved, leaving empty shells.

Biotite occurs as thin flakes and is dispersed randomly throughout the sands. Pyrite also is present but commonly is altered to hematite. As in the Westwater Canyon sands, magnetite and ilmenite are absent.

The authigenic minerals present in the Poison Canyon sandstone are the same as in the Westwater Canyon sands.

Structure

There is a striking contrast between the structure of the north and south sides of the mine. The north side has virtually no structural discontinuities, whereas the south side is extensively faulted.

The north side is cut by several small normal faults, with an occasional reverse fault present. Most of these faults are accompanied by a thin zone of fault gouge. All of the faults are post-ore; the ore bands are always offset by the faults. No ore has been found along the fault planes. The majority of the faults are high angle, with dips of 50 to 85 degrees. Fault planes strike consistently from N. 10° W. to N. 40° E., with an average strike of N. 10° E.

An interesting structural feature present on the north side is a subtle monocline on the northeast edge of the orebody. To the extent that it could be determined from the mine workings, the monocline is approximately 100 ft (33 m) long and 30 ft (10 m) deep. Whereas the average dip of the beds in the mine is 3 degrees, the beds along the monocline dip at an average of 35 degrees in a N. 40° E. direction. The monocline dies out rapidly downward and is not present in the mine workings 25 ft (8 m) below.

The south side of the mine is more intensely faulted than the north side. There are several faults or fault zones present with displacements of up to 75 ft (25 m). In an east-west direction across the middle of the orebody, a series of northward-striking faults causes the strata to be stepfaulted down to the east (fig. 3). The total displacement across the fault series is about 93 ft (31 m). All of these faults are normal, with very steeply dipping fault planes (65-85° E.). Strike is generally in a northerly direction, with a range from N. 10° W. to N. 20° E. In addition to these major faults, there are minor faults with displacements from several inches to 3 ft (about 8 cm to 1 m). All of these faults are post-ore and are probably of Laramide age. The trend of the faults is to the north-northeast, and they are probably associated with a northeast splinter of the San Mateo fault zone.

Sedimentary structures and features

The sandstones exposed in the mine workings exhibit several types of sedimentary features and structures. The Westwater Canyon sandstones and the Poison Canyon sandstones have in common channel-fill crossbedding, foresets, graded bedding, horizontal bedding, and scour-and-fill features. These features are more abundant and conspicuous in the Westwater Canyon sands than they are in the Poison Canyon sandstone. Sedimentary features and structures that are common in the Westwater Canyon sands but lacking in the Poison Canyon sandstone are channel-lag deposits, slump features, mudstone-cobble conglomerates, and trash piles.

Systems of channel-fill crossbedding can vary greatly in size, ranging from 1.2 inches (3 cm) thick and 1 ft (.3 m) across to nearly 3 ft (1 m) thick and 16 ft (5 m) long. In these systems, several individual channels usually are present, which are filled by trough-shaped beds. These beds range from ¼ to 1¼ inches (about 1 to 3 cm) in thickness. Frequently, some grading exists within each bed, with subtle changes from coarser to finer material. This sequence is repeated up through the trough. Overall, the sorting is moderate (Folk, 1968) within the graded beds.

Foreset sequences in the mine range in size from 5 inches (12 cm) high and 3 ft (1 m) across, to 1 ft (30 cm) high and 20 ft (6 m) across. Commonly, a flat erosional surface separates sequences of foresets stacked on top of one another. Within each sequence, the individual sets are about 1-2 inches (2-5 cm) thick. Graded bedding is observable, with the coarser grains confined to the basal layer. The sorting is rather poor, with fines distributed through the foresets.

A locally conspicuous feature that rarely is exposed in the mine is a channel-lag deposit. This is a concentration of gravel and very coarse sand at the base of a channel-scour feature. Channel-lag deposits as much as 1 ft (0.3 m) thick can be traced for up to 15 ft (5 m).

Lag deposits contain the largest fragments found in the mine. The gravel ranges up to 1 inch (2.5 cm) in largest dimension, with the average size being about ¼ inch (.6 cm). The gravel commonly is composed of chert, pink feldspar, granite, and claystone fragments. This coarse layer is moderately to well sorted (Folk, 1968), apparently due to winnowing out of finer material; sorting becomes poorer upward. Organic material, such as pieces of carbonized branches, leaves, and reeds, commonly is concentrated about a foot above the basal layer, apparently deposited after all the fines were winnowed out.

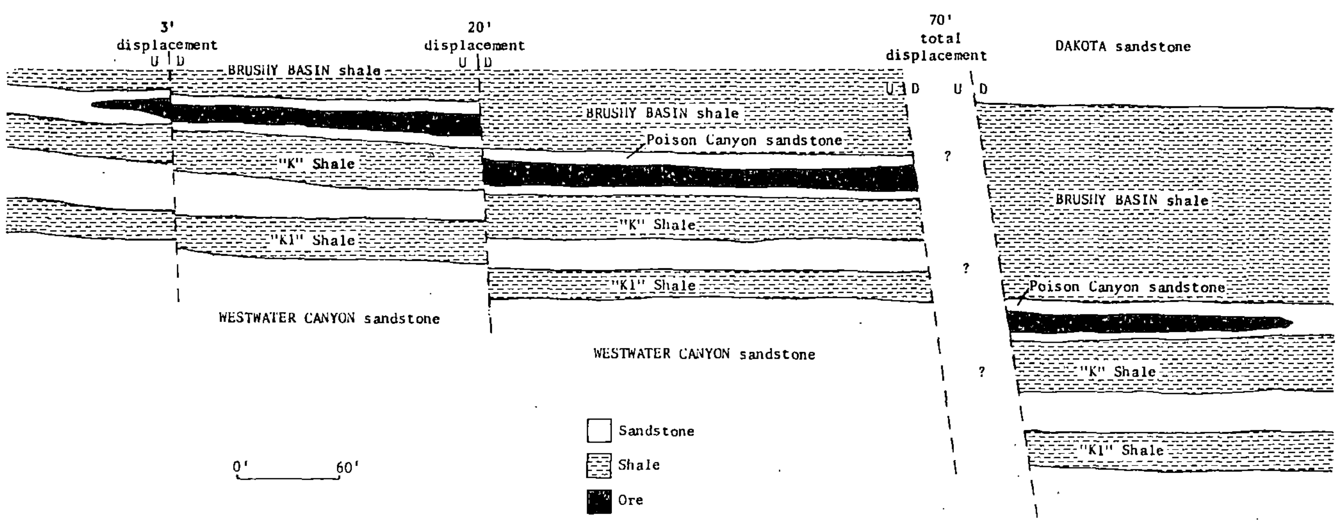

FIGURE 3—East-west cross section looking north in south-side orebody; notice the extensive faulting.

Graded beds are sedimentation units characterized by a gradation in grain size, from coarse to fine, upward from the base to the top of the unit. Pettijohn (1957) discusses the two types of grading: One type is a decrease in grain size upward resulting from the addition of successive increments of material, each finer than the preceding; these increments are probably the product of sedimentation when a current gradually decreases in velocity and competence. In the second type, finer material is distributed throughout, with coarser grains gradually decreasing in abundance upward; this type is a product of sedimentation from a suspension in which all grain sizes are carried and out of which they settle.

This second type of graded bedding is apparently the dominant type present in the sands exposed in the mine; however, this feature is subtle and not easily seen. This grading is pervasive throughout the horizontally bedded sands. Each bed incorporates a sequence of coarser to finer material, repetitive over several feet vertically. In a particularly good exposure, a 2-ft (0.6-m) sequence of coarse sediment had thin beds, 1-2 inches (2-5 cm), of much finer material interlayered within it. The change from the fine to the coarse sand was abrupt—almost knife sharp—but this is rarely seen.

Reverse-graded bedding, where the finer material grades upward into the coarser material, was not observed in the mine exposures.

The most abundant and conspicuous type of bedding present in the Westwater Canyon sands is evenly layered sand composed of parallel and almost horizontal sand layers up to 1 inch (2.5 cm) thick. Individual layers are usually horizontal or slightly inclined owing to deposition on originally inclined surfaces. The layers commonly can be traced laterally up to 12-15 ft (4-5 m). Bedding is commonly marked by repeated sequences of graded beds. Bedding ranges from very thin bedded to thin-bedded (Reineck and Singh, 1975).

The fine- to medium-grained sandstones show the best developed horizontal bedding. Occasionally, a layer of coarse sand 0.4-0.8 inch (1-2 cm) thick is present, interlayered with the normal sequence of bedding. This feature is probably due to deposition during a single flood stage. Different sets of evenly laminated sands are frequently separated from each other by very low angle erosional surfaces.

Scour-and-fill structures range in size from 1 to 20 ft (30 cm to 6 m) across. The contact with the lower sand bed is concave upward, formed by the trough shape of the eroding channel. The channel-fill sand sequence usually extends upward for up to 3 ft (1 m) to where another scour-and-fill feature is present or the horizontal bedding style is resumed.

Ripple marks, or more correctly, casts of ripple marks, have been observed in only one small area within the mine. These small-scale ripples have a height of approximately 0.1 inch (2 mm) and a length of about 1¼ inches (3 cm). The size of the ripples and their formation in a fine-grained sandstone indicate that they formed in a quiet-water environment.

Current lineation, a bedding-plane feature consisting of a streamlining effect of sands grains on smooth bedding planes, is extremely rare. Only one set of lineations was observed, probably owing to the very poor bedding-plane exposures in the mine.

Slump structure is a general term that includes all the penecontemporaneous deformation structures resulting from movement or displacement of already-deposited sediments, mainly under the action of gravity (Reineck and Singh, 1975). Slumping of a sediment mass may result in the breakage and transportation of sediment, producing a chaotic mixture of different types, such as mud-fragment clasts embedded in a sandy matrix or vice versa.

Slump structures are abundant locally in the mine. Large, angular claystone clasts or galls in a mixture of coarse-grained sandstone are not unusual. These slump structures, produced by gravity, probably originated on the oversteepened banks of a channel. Occasionally, thin claystone layers are disrupted, and the resulting angular clasts, up to an inch (2.5 cm) long, are intermixed with sandstone. Distorted or contorted bedding within the sandstone beds is not a common feature.

Squyres (1970) coined the term *trash piles* for large, local accumulations of small carbonized plant fragments within the Westwater Canyon Sandstone. These features are also abundant in the sandstone horizons of the Johnny M mine. The trash piles are large sedimentary accumulations up to 30 ft (10 m) wide and 10 ft (3.1 m) thick of various types of carbonized plant remains, such as reeds, grasses, and small branches. The matrix is usually a poorly sorted, gray, very friable, fine- to medium-grained sandstone that lacks any distinctive bedding. The organic debris tends to be uniformly distributed throughout the trash pile.

Conspicuously present in several sandstone units are claystone clasts, commonly called clay galls. Sizes range from 1/8 inch to 2 inches (0.3 to 5 cm) and may be even larger. The galls tend to be subangular and elongate. The long dimension of the galls, especially the small ones, is conformable with the bedding planes, giving them the appearance of being deposited along with the sand grains.

In addition to the smaller clay galls, claystone clasts are present in zones that range up to 3 ft (1 m) thick and tens of feet in lateral extent. Here are found large clasts, up to 2 ft (0.6 m) long, which represent subangular fragments of once-thick claystone accumulations. These accumulations broke up as a result of differential compaction prior to lithification. These galls must have formed in situ, since they are much too large to have been transported any significant distance. Sand usually fills the interstices between the galls.

Paleochannel directions

Oriented sedimentary structures are abundant in the mine workings of the Johnny M. These structures include foreset dip azimuths, the long axis of channel scours, the axis of channel-fill crossbeds, and the long-axis orientation of trees and bones. The directions of these sedimentary features are generally quite consistent in any particular channel, as well as throughout large regions of the mine.

Directional data from all areas of the mine were collected to determine major stream-flow directions in this part of the Morrison Formation. This data was then analyzed by a computer program for vector analysis of paleocurrent directions. The result indicates that most of the stream systems that deposited the sediments present in the Johnny M flowed in a predominantly easterly direction, with a slight component to the south (figs. 4a, b).

Environments of deposition of the Morrison Formation

The Westwater Canyon Sandstone Member of the Morrison Formation was formed by an aggrading system of low-sinuosity, wide, braided streams. These streams flowed on broad, coalescing alluvial fans emanating outward from a source in west-central New Mexico (Craig and others, 1955). The sedimentologic characteristics of the Westwater Canyon sands are unusual in that they resemble neither well-documented meandering nor braided streams, but appear to fall somewhere in between. The repetitive internal genetic sequence of scoured surface–trough filling–horizontal stratification–clay drape is not typical of meandering-stream deposition. The sandstone units are widespread; if they did not originate as superimposed point-bar deposits, they must have been deposited by shallow, widespread river systems containing smaller scale, braided or anastomosing streams.

While the major flow of the fluvial system was to the north and northeast, filling and choking of these channels probably caused braided, perhaps ephemeral, distributaries to spill laterally off the flanks of the alluvial fan. These newly created streams would then yield the easterly depositional trends that are evident

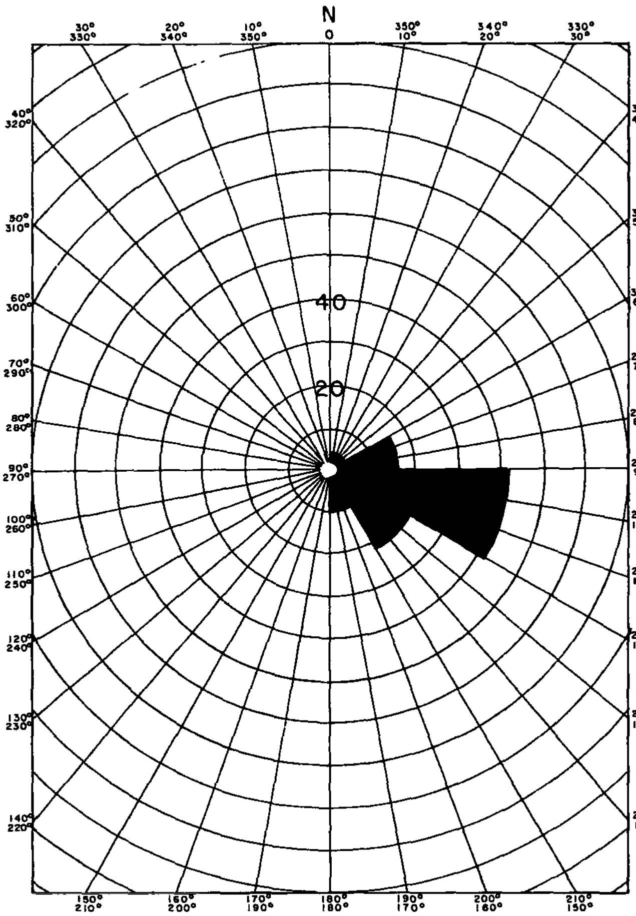

FIGURE 4a—ROSE DIAGRAM OF PALEOCURRENT DIRECTIONS IN THE WESTWATER CANYON SANDSTONE Figures (20, 40) refer to number of measurements

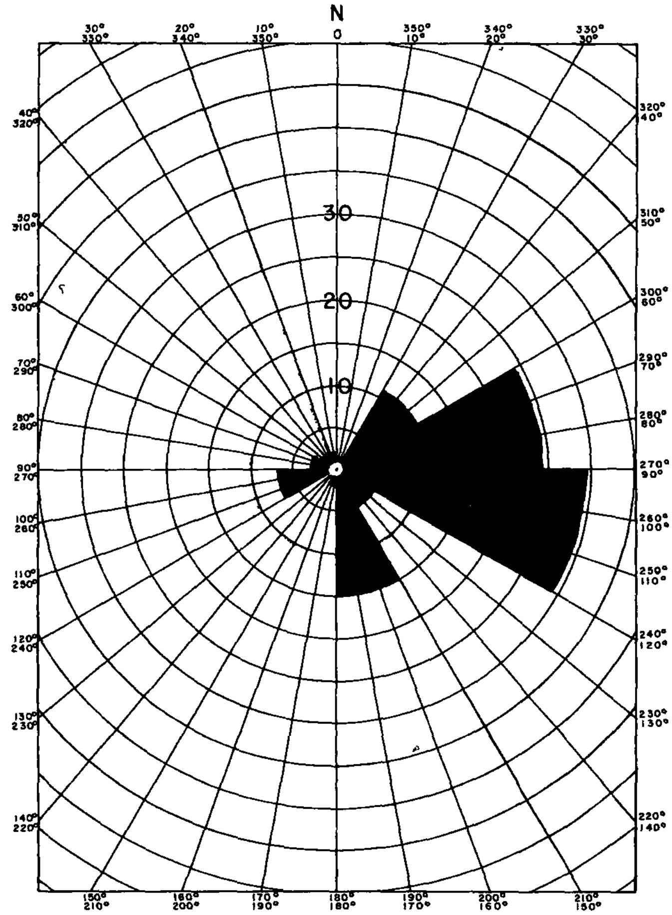

FIGURE 4b—ROSE DIAGRAM OF PALEOCURRENT DIRECTIONS IN THE POISON CANYON SANDSTONE Figures (10, 20, 30) refer to number of measurements

in the Ambrosia Lake district (Squyres, 1970; Rapaport, 1963), in the Johnny M mine, and in the Mount Taylor area (Riese, 1977).

The Brushy Basin Shale Member, with its laterally uniform, blanket-like shale units and random, discontinuous sandstone units, was probably deposited in an environment of strongly meandering streams with extensive floodplains. Large, thick claystone units contain intermixed, discontinuous sandstone units of local to more widespread extent which are of variable texture (gravel to silt). The Poison Canyon sandstone was deposited as a result of one of these large meandering-stream systems. The meandering nature of the stream is supported by the wide dispersion in the paleocurrent indicators (fig. 4b). Thin beds of limestone locally present in the Brushy Basin Shale are probably the result of temporary fresh-water ponds which dotted the floodplains.

Ore deposits

The uranium ore consists of sandstone that is impregnated by a dark, tarry organic substance which coats sand grains and fills interstices. The uranium is contained within the organic material. There are occurrences of organic material that contain no uranium mineralization, but no primary uranium mineralization has been found that is not intimately associated with some type of organic material.

The color of the ore ranges from light gray brown to very dark black—the darker the color, the higher the uranium content. The average grade of the ore from the Johnny M is about 0.40 percent, with concentrations ranging from the economic cutoff of 0.05 percent to over 8 percent U_3O_8.

Vanadium occurs in association with the uranium ore, although in lesser concentrations. Vanadium ranges from .02 percent V_2O_5 in very low grade uranium ore to 1.25 percent in high-grade uranium ore. Molybdenum, copper, selenium, and arsenic (in order of decreasing abundance) are also concentrated with the uranium mineralization.

Westwater Canyon ore

FORM—The overall trend of the orebodies is linear. The thickness of an orebody varies; the ore is not confined to one specific level in a given sandstone horizon but is usually no more than 15 ft (5 m) thick at any one location. The lateral extent of an orebody is more predictable than is the thickness. This fact can be well demonstrated in mine-drilling programs (see Fitch, this volume) where no ore is encountered laterally outside the defined regions of the orebody, whereas ore is sporadically encountered above and below a major orebody.

The orebodies are not one continuous zone of uranium ore; they consist of individual ore pods that occur in various shapes. The dominant ore-pod form is that of elongated tongue-like lenses that range from 3 ft (1 m) to over 30 ft (10 m) long (fig. 5). These pods are commonly lenticular in cross section with a length-to-width ratio from 2:1 to 25:1. The thickness of any given individual ore pod is usually less than 5 ft (1.6 m). Numerous thin ore pods may occur together, resulting in complex forms.

BLANKET ORE—Blanket ore is a term given to very long, thin ore pods that are irregular in ore content and unpredictably undulate or roll through the sandstone horizon. The pod usually deviates only about 6 ft (2 m) from the horizontal plane. This blanket ore commonly is situated in the lower part of the exposed

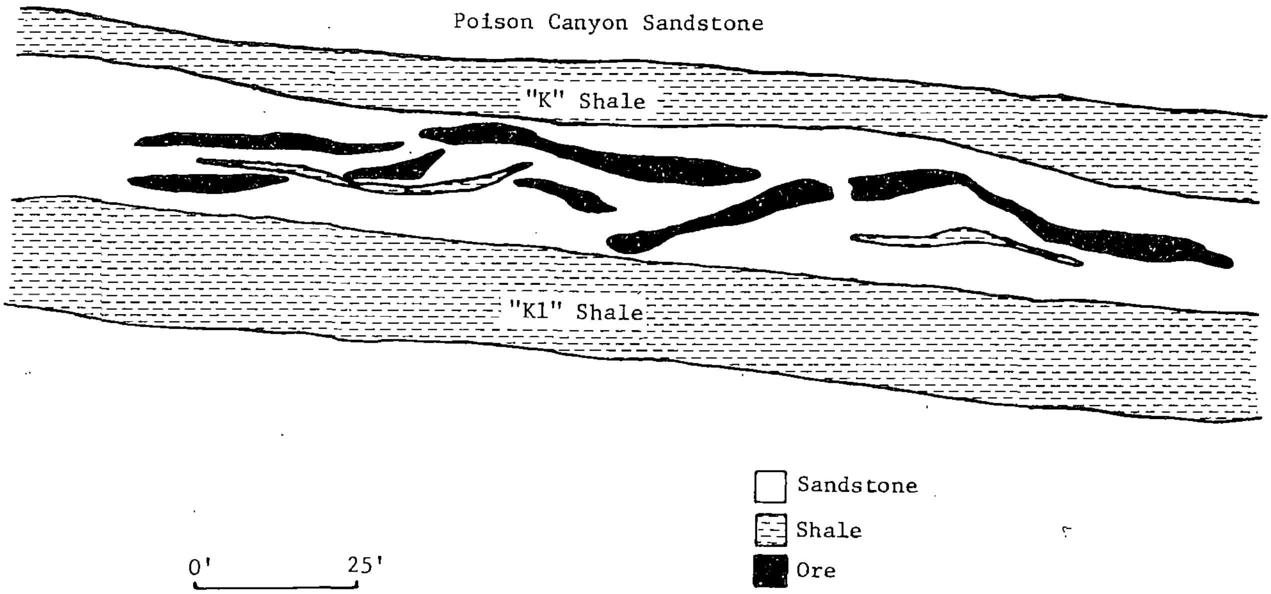

FIGURE 5—East-west cross section, looking north in Westwater Canyon Sandstone ore; notice the form of the ore pods.

sandstone layer, usually occurring atop a claystone zone, if one is present. Calcite cement usually separates the ore from the claystone.

Difficulty in viewing the ore pods in three dimensions means that a trend is not always obtainable; when an ore-pod trend is visible, the elongation usually is parallel or subparallel to the overall trend of the entire orebody.

The ore pods, especially the smaller ones, are generally uniform in ore composition and have sharp boundaries with the surrounding barren rock. The uranium content of the sandstone at the ore boundary can decrease several hundredfold in a distance of 2 inches (5 cm). Some contacts are knife sharp. Some of the pods are patchy and ill defined, and these generally are much lower in U_3O_8 content than the more uniform ore pods. The smaller, more homogenous ore pods are consistently the richest ones, often containing over 1 percent U_3O_8. The richer ore pods also contain the most calcite cement. The cement usually extends beyond the ore boundary for 1-2 ft (0.3-0.6 m) and then gradually dies out into more friable, barren sandstone. The larger ore blankets are more friable than the smaller pods, but they are much better indurated than the average barren sandstone.

ORE ROLLS—The term roll, synonymous with ore roll, is applied to any curving surface which cuts across the bedding of the host rocks (Squyres, 1970). Crescent-shaped ore pods, similar to the overall geometry of the classic Wyoming-type roll, occur in the Johnny M mine, but they are very rare and much smaller. These rolls may be as much as 12 ft (4 m) long and 4 ft (1.3 m) high. One roll observed had a distinct head with two tails extending outward. Tails are usually interpreted to point in the direction from which the ore fluids came. The roll was elongated nearly parallel to the trend of the main orebody. The convex side (front) of the roll had a sharp contact with barren, bleached sandstone, whereas the concave side (back) of the roll had a more diffuse contact. Ore was evenly distributed throughout the roll. The tails tended to feather out into the host sands. Sandstone immediately adjacent (front and rear) to the ore roll was bleached tan gray, whereas sandstone further out around the roll was gray green, suggesting that the bleaching effect was probably associated with the formation of the ore roll.

DIRECTIONAL FEATURES—While most ore pods are situated in a sandstone host with no apparent connection to any specific feature, an occasional ore pod is intimately associated with fossil trees. The ore is formed as a halo around the tree, with a distinctive tailing effect pointing in the presumed paleocurrent direction. There is much more ore on the lee side of the tree than on the up-current side. The fossilized log itself is not necessarily mineralized, but a thin crust around the log usually contains some mineralization. This tailing effect is an uncommon feature, but where present, the trend of the tail is parallel to subparallel to the overall trend of the orebody.

IRON BANDS—Accompanying nearly every well-defined, uniform ore pod is a red band of apparently oxidized sandstone. This band is usually present along all or most of the periphery of the pod; and if not, it is commonly restricted to the front and/or bottom of the pod. This red band, which usually is continuous, never actually comes in contact with the ore, as there is always a thin (0.5 inch, 1.3 cm) space between the red band and the ore. The total iron content of this band typically is higher than the total iron content of the ore and surrounding sediments.

CONCENTRIC ORE POD—Only one example was observed of a spherical pod of high-grade ore, which was completely enveloping an extremely well-cemented (by calcite) sphere of low-grade ore. The lithology of the host sandstone, medium-grained arkosic sand, was the same across the whole sphere. The whole pod was well cemented, but the center was more indurated than the richer ore. The calcite cement was pervasive throughout the whole area, making the corresponding red band around the sphere well indurated also. The outer ore assayed 4.0 percent U_3O_8, whereas the central part ran 0.2 percent—by no means barren, but considerably less than the surrounding ore. The contact between the high- and low-grade ore was almost knife sharp.

Poison Canyon ore

FORM—Poison Canyon ore differs from Westwater Canyon ore in that it is more massive and very rarely occurs as the small individual lenses so common in the Westwater Canyon. Individual ore pods are much more extensive, continuous, thicker, and more uniform in the Poison Canyon. Ore pods may be 50 ft (15 m) long, 25 ft (8 m) wide, and up to 6 ft (2 m) thick, although the average ore pod is smaller. The length-to-width ratio ranges from 3:1 to 10:1. Sandwiched between the K shale and the Brushy Basin, the ore may extend the entire thickness of the Poison Canyon sandstone, about 12 ft (4 m). The best way to describe the ore form is sheet- or manto-like. The trend of the sheets of ore is parallel to the overall trend of the orebody.

Where the ore does not occur as one mass across the entire thickness, it is usually a thin layer up to 2 ft (0.6 m) thick at the base of the Poison Canyon, overlying the K shale. Ore can be found anywhere in the sandstone horizon—in the middle with barren sand on either side, or in the upper part directly below the Brushy Basin. When the ore is near the K shale, it is never in direct contact with it; there is a calcite-cemented zone up to 4 inches (10 cm) thick that separates ore and shale.

Besides the basic shapes and forms expressed by the Poison Canyon ore, there are other differences in comparison to the Westwater Canyon ore. The overall grade of the Poison Canyon ore is lower than the grade of the Westwater Canyon ore. Calcite cement is pervasive throughout the Poison Canyon, but the ore is not quite as well indurated as Westwater Canyon ore. Locally, the ore is quite hard, but overall is more friable than the Westwater Canyon ore. The most obvious difference between orebodies in the Poison Canyon and the Westwater Canyon is the significant lack of organic detritus such as trees, bones, and trash piles in the Poison Canyon sands. Only two or three pieces of carbonized debris have been found in the Poison Canyon sandstone.

MINERALIZED CLAY GALLS—A few clay galls impregnated with uranium mineralization are present. Usually this occurs only in clay galls that are isolated within massive pods of ore.

Features such as ore rolls and directional indicators do not occur in the Poison Canyon. The iron bands common around the ore pods in the Westwater ore are rare and poorly developed in the Poison Canyon ore.

Relation to stratigraphy, sedimentary features, and structure

Orebodies in the Johnny M mine are not subject to any definite stratigraphic control, although the overall orientation of the orebodies and the orientation of most of the ore pods is consistent with the orientation of fluvial sedimentary features. While no one major stream channel has been or can be accurately mapped, the sandstone near and in the orebodies tends to be more prominently crossbedded and coarser grained, contains more fossil detritus, and exhibits more channel-associated characteristics than the sandstones at a greater distance from ore. The ore-bearing horizons are inferred to occur in at least part of a fluvial channel complex.

Individual ore pods can occur 1) suspended within thick sandstone beds separated from adjacent sedimentary surfaces by a few feet of barren sandstone, 2) resting on the upper surface of a claystone bed, 3) intermixed with a claystone-cobble conglomerate, or 4) localized on a laterally persistent scour surface. Thin layers of ore that occur in thick sandstone beds are more apt to be associated with erosional surfaces and thin claystone zones.

Although ore locally does conform to bedding or to an erosional surface, ore pods consistently transect all types of sedimentary structures, including lithologic changes, crossbedding, and scour surfaces. The ore boundary that transects sedimentary features is usually sharp, and there is no change in grade or morphology of the ore across the feature. The most common sedimentary feature that the ore transects is lithologic variation, most noticeably a change from a coarse-grained sandstone to a fine-grained sandstone. Typically, ore that closely follows bedding or another sedimentary feature eventually dips down and crosses that feature. Overall, no small-scale sedimentary feature has been observed that exerts any significant control on the emplacement of ore.

Claystone zones commonly separate ore pods that are stacked. Interfingering of ore pods occurs where ore is at different levels in close proximity to one another, so the ore is not confined to one specific layer in the bed. The ore pods are randomly distributed throughout the orebody, indicating the lack of specific beds or sedimentary features controlling the ore emplacement.

Two features appear to have some influence on the location of ore pods. Persistent claystone zones usually exist as a basal barrier to blanket ore. Tracing these claystone zones may lead to more ore. Trash piles commonly are in close proximity to major ore pods, the pods lying in the presumed down-current direction. These trash piles are believed to be the major source of the humate material associated with the uranium ore.

Orebodies that occur in the Poison Canyon sandstone are under much greater stratigraphic control. The Poison Canyon sandstone, which has an average thickness of 12 ft (4 m) in the mine workings, consistently is bounded by two impermeable shale layers, the K shale below and the shales in the Brushy Basin above. Any ore present exists between these two shale layers. The majority of the ore occurs in the basal part of the horizon. A correlation seems to exist between ore occurrence and a persistent coarse-grained sandstone bed within the Poison Canyon; the ore is not strictly confined to this one particular bed, but it appears to be situated preferentially in or very close to the bed.

The relation between ore and faulting is very straightforward: faults cut and displace ore, with no apparent ore movement along the fault plane (fig. 3). The extensive faulting does affect mine planning, as the fault zones are avoided owing to their weakness. Faulting consistently displaces Poison Canyon ore down to the east, which also affects mining.

Associated jordisite

Squyres (1970) stated that a black amorphous substance identified as jordisite (MoS_2) exists in close association with primary orebodies in the Grants region. Squyres implies that jordisite is quite abundant in the Ambrosia Lake district; however, significant amounts of jordisite are not present in the Johnny M mine.

Where jordisite does occur in the mine, it is much more abundant in association with Poison Canyon ore than with Westwater Canyon ore. Jordisite in the Westwater Canyon occurs in a feathery pattern, selectively impregnating certain laminae of the bedded sandstone adjacent to an ore pod. The jordisite feathers extend outward peripherally from the ore pod but are never in direct contact with the ore; an inch (2.5 cm) or so of barren sandstone separates ore and jordisite.

Jordisite associated with the Poison Canyon ore is much more massive and extensive. Instead of feathery masses, the jordisite occurs as layers, often 6 inches (15 cm) thick but rarely over 1 ft (30 cm) thick. Here, also, a narrow band of barren sandstone separates ore and jordisite.

The jordisite, typically brownish-gray, has a molybdenum content ranging from 0.03 to 0.08 percent and a U_3O_8 content as high as 0.06 percent. In general, jordisite is locally abundant within certain ore pods but is volumetrically unimportant in the mine workings.

Ore controls

SEDIMENTARY CONTROLS—The one major sedimentary ore control is the presence of a quartz-rich, arkosic, fluviatile sandstone. This type of sandstone is the only host for ore in the Grants region. Within this sandstone are a number of smaller scale features which locally may be important to the depositional control of the ore: diastems, bedding planes, grain size and sorting, calcite cement, and carbonaceous material.

Observations lead to the conclusion that, of these smaller scale features, only carbonaceous material exerts considerable control over ore emplacement. Carbonaceous matter (humate) is present in every sandstone uranium mine in the Grants region (Granger, 1968). All primary ore is coextensive with carbonaceous matter. Granger (1968) also stated that all such carbonaceous material has been at least partially mineralized with uranium; conversely, no uranium of undisputedly primary origin has been found away from carbonaceous matter.

These statements are certainly true of the Johnny M mine. All of the ore that has been or is being mined is intimately associated with black to dark-brown carbonaceous material in the sandstones; no ore has been found in sandstone devoid of this carbonaceous matter. Patches of black material are frequently found that look like ore but actually consist of very low grade mineralization.

STRUCTURAL CONTROLS—Structure has been mentioned as an ore control (Clark and Havenstrite, 1963). In the Johnny M mine there are no structural features that appear to control the ore. The faulting encountered in the mine offsets orebodies as much as it offsets stratigraphic units. Where the ore abuts a fault plane, such minute amounts of ore are contained within the fault plane that virtually no movement of ore after faulting has occurred. Consequently, no stack ore is present in the Johnny M mine. Joints and fractures also crosscut the ore in the same manner as do the faults.

Age of the ore

Several parameters limit the age range of the uranium ore deposits.

STRUCTURAL EVIDENCE—Faulting in the southern San Juan Basin has been related to structural deformation associated with the Laramide (Late Cretaceous–early Tertiary; Kelley, 1963) uplift of the Zuni Mountains. Because orebodies in the Grants region are displaced by some of these faults that radiate northward from the Zuni Mountains, the uranium-ore deposits are inferred to have formed before the faulting occurred, and a minimum age of pre-Laramide is indicated for the orebodies.

STRATIGRAPHIC EVIDENCE—Granger and others (1961) have studied collapse structures present in the Ambrosia Lake district. They concluded that ore, which is localized around the cylindrical features, is probably pre-Laramide, the inferred age of the collapse structures.

The Dakota Formation and the upper 30 ft (10 m) of the Morrison Formation are not displaced by the collapse structures in the Cliffside mine (Clark and Havenstrite, 1963), although beds a few tens of feet lower show full displacements. The collapse structures and the associated ore, therefore, must have been formed during deposition of the Morrison Formation.

Nash and Kerr (1966) established a pre-Dakota age for the uranium ore in the Paguate mine in the Jackpile sandstone. They described a section of ore-bearing sandstone at the top of the Jackpile sandstone that is truncated by a pre-Dakota erosion surface. These geologic relations are clear enough to establish a definite pre-Dakota age for the ore.

RADIOACTIVE DATING—In 1963, Miller and Kulp, using U^{235}:Pb^{207} ratios, calculated ages of 210 m.y. for the uranium deposits in Triassic rocks on the Colorado Plateau and of about 110 m.y. for deposits in the Morrison Formation. They concluded that the ore deposits formed soon after deposition of the host rocks. Granger (1963b) estimated an age of about 100 m.y. for the uranium deposits in the Ambrosia Lake district but noted that this is probably a minimum age. R. S. Della Valle (personal communication, 1978) has been engaged in a geochemical study of several orebodies in the Grants region. His preliminary age determinations indicate that the ore deposits become successively younger upsection in the Morrison Formation. The ages obtained range from 150 to 140 m.y., suggesting that the ore formed during or immediately after deposition of the host sands.

Source of the uranium and associated ore elements

The major hypotheses concerning the source of the ore in sandstone-type uranium deposits are: 1) ascending uraniferous hydrothermal solutions, 2) leaching of granitic rocks assumed to be the source of the sediments, 3) leaching of the host sediments by ground water, 4) leaching of volcanic ash deposited synchronously with the host sediments, and 5) leaching of the bentonitic shales (Brushy Basin) stratigraphically above the host sediments by ground water.

The most plausible sources for the uranium are leaching of granitic rocks and volcanic ash. Based on the following arguments, volcanic ash seems to be a more likely source than granitic rock: 1) Granitic rocks are a possible source for most of the ore elements associated with uranium but are probably not an adequate source for selenium and arsenic, whereas volcanic ash probably is an adequate source for all of the elements. 2) Uranium in granite either occurs in accessory minerals (sphene and zircon) and silicates (micas) and is unavailable for ore formation; or it is present along grain-to-grain boundaries and is likely to be released during weathering and then dispersed and diluted in the surface runoff. Uranium in volcanic ash is more likely to be released in an environment favorable to ore deposition. 3) Ground-water data tend to confirm that uranium can be derived from volcanic detritus more readily than from granites.

Of the two theories employing volcanic ash as the source of the ore elements, I strongly prefer the syngenetic model for these reasons: 1) By having the uraniferous air-fall tuffs deposited at or near the same time as the host sands, the uranium is immediately put into a system with favorable environments for ore formation without requiring long transportation. 2) Uranium leached from a bentonitic mudstone (Brushy Basin Shale) 100 ft (33 m) thick, with a very low permeability, and transported by ground water to favorable sandstone horizons below is difficult to accept. 3) If the Brushy Basin Shale is actually the source for all the uranium in the Grants region, why is the Brushy Basin uniformly and anomalously high in uranium? 4) Owing to rainfall during deposition of the Brushy Basin, a substantial amount of the uranium probably would be lost to surface runoff and would not be available later.

The most plausible source of the uranium and associated ore elements in the sandstone-type uranium deposits in the Grants region is volcanic ash; ore elements were released to the host sediments contemporaneously with deposition of these sediments.

Scenario of ore formation

Volcanic ash brought to northwestern New Mexico by westerly wind patterns presumably was derived from extensive volcanic activity in the western United States during deposition of the Morrison Formation (C. E. Chapin, personal communication, 1978). This air-fall tuff would have been deposited in the region where the Morrison sediments accumulated. Deposition of the ash in the fluvial system would have initiated leaching of the ore elements and their subsequent release into the stream water and near-surface ground water. Owing to the wide dispersion of the air-fall tuff, surface runoff would have also contained some ore elements in solution, resulting from leaching of the ash by rainfall.

The fluvial system that deposited the Morrison Formation contained much vegetation. Vegetation accumulated in local backwater swamps, abandoned channels, and on exposed bars. The trash piles would probably have been formed in backwater swamps or abandoned channels that were flood-connected to the active sedimentation system. Constant decay of the organic material would have released humic acids into the fluvial system.

The uranium and ore elements were adsorbed and reduced by the humic acids present (aided by bacteria), and uraniferous-organic complexes formed. These complexes may have formed in the surface waters and easily permeated the recently deposited sands, thereby entering the near-surface ground water. The migration of these uranyl humates would have been impeded by mudstone layers that acted as permeability barriers. Clay galls would not be expected to be mineralized by the uranyl humates because of their lower permeability. The uranyl humates ultimately formed a gel and eventually became insoluble. The uraniferous-organic complexes formed and precipitated at or very near the surface—an inference from our knowledge that some ore bands in the mine are truncated by a channel scour, indicating the ore processes occurred essentially on the surface. Most uranyl-humate complexes migrated into the ground water where they were ultimately flocculated. The various shapes attained by the individual ore pods are the result of the different flow patterns of the ground water.

Since the uranium complexes are envisioned as having formed in the surficial waters, the ore pods might have been expected to conform very closely to the sedimentary structures; this expectation is not confirmed by the Johnny M mine. As the humate complex formed a gel, it migrated in the water and passed through the permeable sandstones. The permeabilty controls would be less effective in the newly deposited and unconsolidated sediments. With time, the migrating gel became more viscous and finally coalesced into the form we see today, with curving boundaries truncating sedimentary structures.

Once buried under sediments, the uranium may have undergone further secondary chemical changes in the course of the long geological processes of coalification and fossilization (Szalay, 1958). Secondary enrichment and mineralization may have taken place, according to local conditions. The host rocks themselves may have undergone changes after burial. The color schemes present in the uranium-bearing sandstones were probably caused by either diagenesis or later ground-water movements.

The factors controlling the time and location of concentration of uranium and other ore elements are humic acids derived from decaying plant matter and deposition of a uranium-rich air-fall tuff or ash. While humic acids probably would have been present during most of the history of the sediment deposition, uranium and associated ore elements would have been present in the waters on an irregular basis, owing to the sporadic nature of air-fall eruptions. This factor would explain why there are barren sand beds located between sands that are ore bearing; no uranium was present in the fluvial system when the barren sands were deposited. While no absolute time can be given for the interval between the deposition of the volcanic ash and the ultimate formation of the ore, the processes seem to be geologically rapid.

Conclusions

1) The fluvial environment in which the host sediments were deposited consisted of a network of aggrading braided streams and meandering streams generally flowing in an east-southeast direction.
2) The carbonaceous matter intimately associated with the uranium ore was originally humic material derived from the decay of plant material occurring in the fluvial environment.
3) The uranium and associated ore elements were derived from volcanic ash deposited contemporaneously with the sediments.
4) Accumulation of uranium and other ore elements took place while the humic acids were migrating in aqueous solution, either at or near the surface.
5) Ore formation was definitely completed during Jurassic time and probably during deposition of the host rocks. The subsequent deep burial, coalification, and faulting of the orebodies were later processes unrelated to ore deposition.
6) The orebodies are localized in paleostream-channel systems, thereby accounting for the linear aspects of the orebodies or trends.
7) The only factors controlling the location and time of ore deposition are the presence of anomalous amounts of uranium ions in the fluvial system and the existence of favorable humic acids to trap and concentrate the uranium and other ore elements.

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